Research Article

Redesign and Structural analysis of agitator shaft for reactor pressure vessel

Sumit R.Desai#*, S.Y.Gajjal# and Kulloli#

#Department of Mechanical Engineering, NBNSCOE, Savitribai Phule University of Pune, Ambegaon (Bk), Pune, India 411041

Abstract

Agitator shaft is important component of agitation system used in reactor pressure vessel. Failure of agitator shaft leads to breakdown of whole plant. The existing agitator undergoes deflection; not suitable for uniform mixing of fluid, also time required for agitation is more. One of the major parameter to increase the overall performance of agitator shaft is to reduce deflection. The work is carried out to reduce deflection by optimizing the design or by using different materials like SS, SS304 and SS305. This dissertation work is aimed to redesign existing single impeller agitator shaft by using SS316 material with double impeller. This results in improved overall performance by minimizing deflection of agitator. Redesigned impeller agitator shaft is modeled using CAD modeling software. Stress analysis of the shaft subjected to combined loading was done using FEA software. These results were compared with experimental values observed by company. It is observed that the deflection of redesigned agitator is 0.8375 mm which is reduced by 14.997 % than exiting agitator.

Keywords: Agitator shaft, Bending stress, Impeller, Reactor pressure vessel, Torsional stress

Introduction

Pressure vessels widely used in reactor technology, the chemical industry, marine and space engineering. A pressure vessel is a closed container designed to hold gases or liquids. Agitators are devices that are used to stir or mix fluids, especially liquids, which is one of the basic mechanical process engineering operations. Industrial agitators are machines used in industries that process products in the chemical, food, pharmaceutical and cosmetic industries, in a view of mixing liquids together, promote the reactions of chemical substance, keeping homogeneous liquid bulk during storage. So as to impart modifications if necessary to keep the vibrations of the vessel within the limits from the point of view of proper functioning of the vessel and safety issues. Agitators are used for the homogenization of liquids or liquid-solid mixtures by generating horizontal and vertical flows

Agitator shaft is a rotating member usually of circular cross-section which is used for agitation or mixing purpose. Elements such as impeller, coupling, bearing are mounted on the shaft. In design it is usually possible to locate the critical areas, size these to meet the strength requirements, and then size the rest of the shaft to meet the requirements of the shaft-supported elements. Agitator shaft is a critical component used in reactor pressure vessel. It carries a load of impellers.

Along the years, many unexpected failures of equipments and various machines have occurred throughout the industrial world. A number of these failures have been due to poor design. However, it has been discovered that many failures have been caused by preexisting notches or flaws in materials that initiate cracks that grow and lead to fracture.

In the chemical industry, many types of vessels, which are also called as reactor vessel, with agitator, are being used largely for the purpose of homogeneous mixing of the product. Since a chemical plant runs continuously for 24 hours per day, to achieve optimum plant reliability is the main goal of the chemical industry. Thus, in case an equipment failure that may occur at unexpected instant results in production shutdown and its related costs. Such events occur predominantly in rotating equipment, e.g. in large agitators. Therefore, they are responsible for significant loss of plant availability. In fact, an agitator shaft with a notch or scratch can be cracked and leaded to failure easily under the combined stresses created by fluctuating forces during operation.

When the existing agitator is not suitable and does not provide a comfortable working condition to the workforce thus creating problems in the output of then different parameters of the organization efficiency like quality, quantity, delivery schedule and work force satisfaction.

Literature review reveals that the previous work carried out on Agitator shaft was focused on failure

*Corresponding author: **Sumit R.Desai**

aspect. In this paper, Agitator shaft design modification carried out for selection of another material, motor selection, mounting of agitator, no. of impeller used and analyzed for structural analysis

2. Material Selection

The agitator shaft was made from a standard AISI type 316 stainless steel that is Austenitic grade. Austenitic stainless steels are the most widely used and while most are designated in the 300 series. Especially types 304 and 316 are highly ductile and though grades and they are utilized for a broad range of equipment and structures. Austenitic grade steels are non-magnetic and non heat-treatable steels that are usually Annealed and cold worked.

They provide excellent corrosion and heat resistance with good mechanical properties over a wide range of temperatures, respond very well to forming operations, and are readily welded. When fully annealed, they are not magnetic. Austenitic grade steels have γ- austenite structure which can dissolve up to 2 % C in solid solution and has FCC (face-centered cubic) crystal lattice. The Chemical Composition and some Mechanical Properties (acc. to ASTM) of Type 316 SS are given in Table 1 and Table 2.

Table 1 Chemical Composition of AISI 316 SS

Element	Weight, %
C	0.08
Cr	18-20
Ni	8-10
Mn	2.0
Si	0.75
P	0.045
S	0.03
Iron	Bal.

Table 2 Mechanical Properties of SS316 Annealed

Property	Unit	Value
Density	kg /m^3	7800
Poison's Ratio	-	0.30
Elastic Modulus	GPa	193
Shear Modulus	GPa	86
Tensile Strength	MPa	515
Yield Strength	MPa	205

3. Design of agitator

Power Requirement for Agitator

The power consumption in an agitated vessel is a function of the variables that is:

$P = \phi\ (n, D, g, \mu, g, \rho)$
Where:
n: speed
D_a: impeller dia.

μ: viscosity
g: acceleration of gravity
ρ: density

A. Power Number (Np)

The *Power Number (Np)* from which the power will be calculated can be written like this:

$Np = P*g\ /n^3 D_a^5\ \rho$

$n D_a^2\ \rho/\ \mu = N_{Re}$ Reynolds Number

$n^2 D_a/g = N_{fr}$ Froude Number

$N_{Re} = 3.89 \times 10^5$
$N_{Re} > 10000$ (flow is fully turbulent)

Because the flow is fully turbulent, power number is only function of shape factors.
From the graphs given in (Chem. Eng. Handbook, 1973)

From power curve
$$\frac{W}{Da} = 150/900$$
$$= 1/5$$

Np = 4 found for impeller with two flat blades

B. Power Required
$P = Np \times \rho \times N3 \times Da^5\ /\ g \times 75$
$P = P_1 + P_2$
$= 10.582$
Where
P = Total Power Required
P_1 = Power required to 1st impeller
P_2 = Power required to 2nd impeller

Also consider 10% gland losses and 20% transmission losses
P = 10.927hp
So selected Next std.
P = 15hp   ….….   Motor selected

2. Design of Agitated shaft

A. Rated torque

$$P = 2\pi N T_r / 4500$$
Where
P = Total Power Required
N = Agitated speed in rpm
T_r = Rated torque
T_r = 93417.03Nm

B. Design of shaft on Pure Bending

By bending theory
$M_b = \pi/32 \times 6_b \times d^3$
Where M_b = Bending moment
6_b = bending stress
$F_m = T_m/(0.75 \times R_b)$
Where F_m = impeller force
T_m = Max torque

R_b = Radius of impeller blade

F_{m1} = 2753.15N

Bending Moment

$M_{b1} = F_{m1} \times l_1$ = 3303600Nmm

$M_{b2} = F_{m1} \times l_2$ = 6882500Nmm

Total M_b

$M_b = M_{b1} + M_{b2}$ = 10186100Nmm

$M_b = \pi/32 \times 6_b \times d^3$

d = 83.22mm

C. Design of shaft subjected to combine twisting moment and bending moments

By Maximum shear stress theory (ASME Code)

$\zeta_{max} = 16/ (\pi \times d^3) \sqrt{(M_b{}^2 + M_t{}^2)}$

Where ζ_{max} = max shear stress

M_b = bending moment

M_t = twisting moment

$d^3 = 16/ (\pi \times \zeta_{max}) \sqrt{(M_b{}^2 + M_t{}^2)}$

d = 85mm

D. Design of shaft based on Critical Speed

Agitator speed not within ±30% of critical speed

Deflection due to 1st impeller

$\eth_1 = F_{m1} \times l_1{}^3 / 3EI$

$\eth_1$ = 3.026mm

Critical Speed (N_{c1})

$N_{c1} = 946/ \sqrt{\eth_1}$

= 528.334rpm

Critical Speed (N_{c2})

$N_{c2} = 946/ \sqrt{\eth_2}$

= 175.68rpm

Critical Speed of whole system

$1/ N_c{}^2 = 1/ N_{c1}{}^2 + 1/ N_{c2}{}^2$

N_c = 166.70 rpm

Actual speed of agitator =115rpm which is 68.98% of critical speed, hence necessary to increase value of critical speed.

So,

Choose next standard d = 90mm .... shaft diameter

Actual speed is 61.98 % of critical speed, therefore selected 90 mm dia. of agitator shaft is satisfactory, which is not between 70 to 130 %.
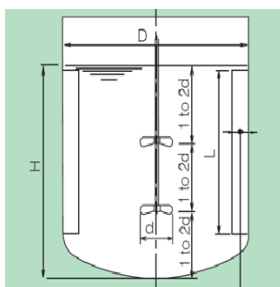

Figure 1 Agitator mounted at the center

Agitator mounted at the center of tank and baffles plates are attach on inner walls of tank to crate vertical

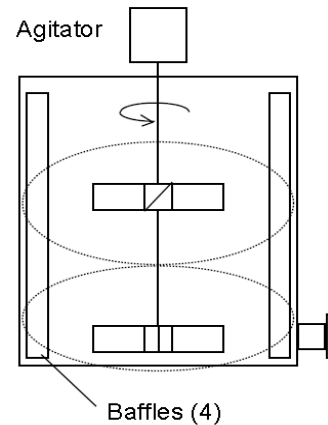convection and turbulence. Baffles are needed to prevent vortexing and rotation of the liquid mass as a whole.

Figure 2 Agitator shaft with Baffles

Antiswirl baffles are required in larger industrial fluid-mixing operations. Baffles are used for center-shaft, top-mounted mixers to prevent vortexing. Baffles also promote top-to-bottom turnover and represent good mixing practice. The most usual arrangement is to have four baffles paced at 90^0.
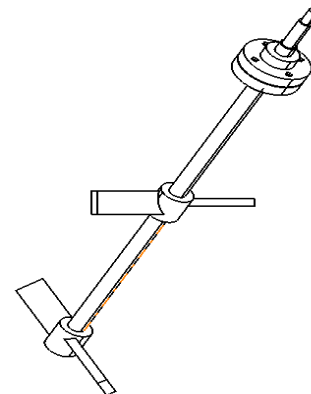

Figure 3 CAD Model of Double impeller Agitator

4. Structural Analysis

Static analysis calculate the effects of steady loading condition on a structure, while ignoring inertia and damping effects, such as those caused by time varying loads. A static analysis can include steady inertia loads such as gravity and rotational velocity and varying loads that can be approximated as static loads. Static analysis determines the displacements, stresses, strains, and forces in structure or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is the loads and structures responses are assumed to vary slowly with respect to time. A static analysis result of structural displacements, stresses and strains and forces in structures for components caused by loads will give a clear idea about whether the structure or components will withstand for the applied maximum forces. If the

stress values obtained in this analysis crosses the allowable values it will result in the failure of the structure in the static condition itself. To avoid such a failure, this analysis is necessary.

Assigning material properties: Material properties Young's modulus & Poisson's ratio are defined. Also other properties like coefficient of expansion, coefficient of friction, thermal conductivity, damping effect, specific heat etc. are defined if required
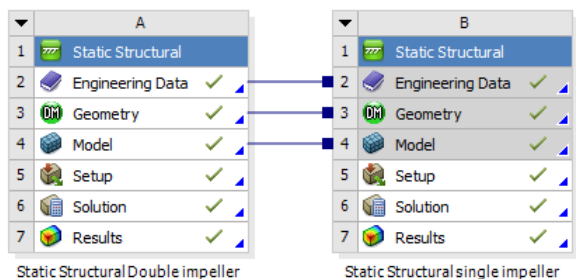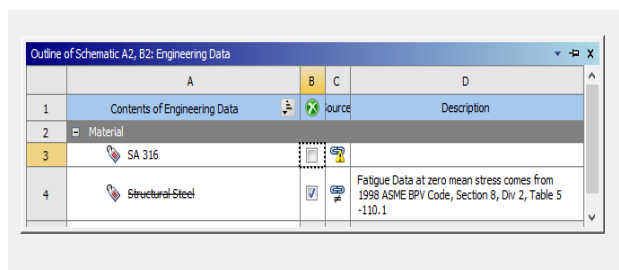

Figure 4 Static structural Analysis

Figure 5 Engineering Data
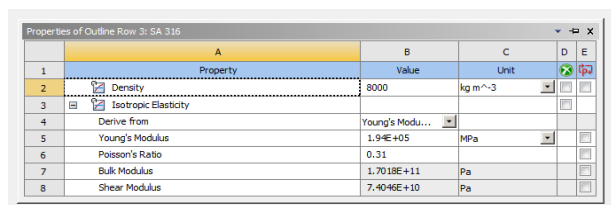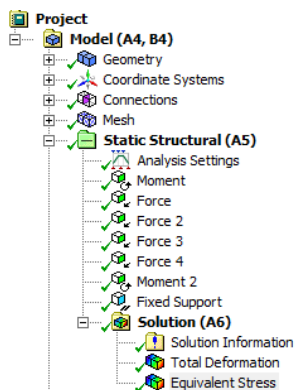

Figure 6 Properties of Material

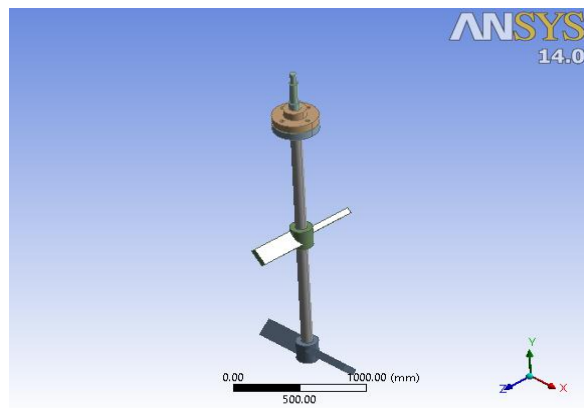**Figure 7** Flow diagram of Double impeller shaft

Figure 8 CAD Geometry of Double impeller Agitator Shaft

Mesh generation is a process of dividing the structure continuum into a number of discrete parts or finite elements. If the mesh is finer, the results are also better but the analysis time is longer. Therefore, a compromise between accuracy & solution speed is usually made.

Fine mesh was used to increase the number of elements at the vicinity of the critical points. The auto mesh generator uses an algorithm that minimizes element distortion. 3-D linear tetrahedral solid 186 and solid 187 elements with global element size of 30mm and local element size of 10mm were considered at the critical locations. After discretization 578501 nodes and 129033 elements were created
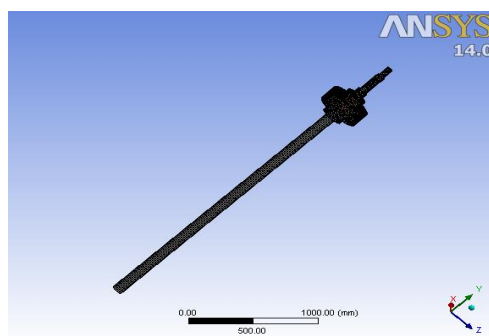

Figure 9 Meshing of Double impeller Agitator shaft

Apply loads: - Some types of load are usually applied to the analysis model. The loading may be in the form of a point load, pressure or displacement in a stress analysis.

Applying boundary conditions: - If you apply a load to the model, then in order to stop it accelerating through the computer's virtual ether (mathematically known as a zero pivot), at least one constraint or boundary condition must be applied. Structural boundary conditions are usually in the form of zero displacements.
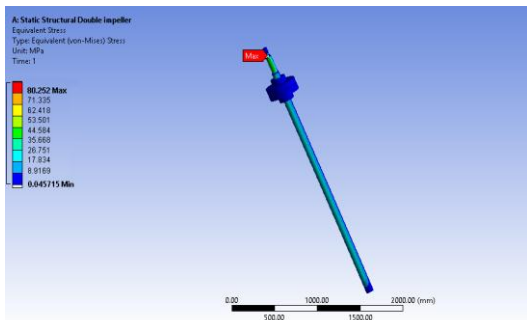
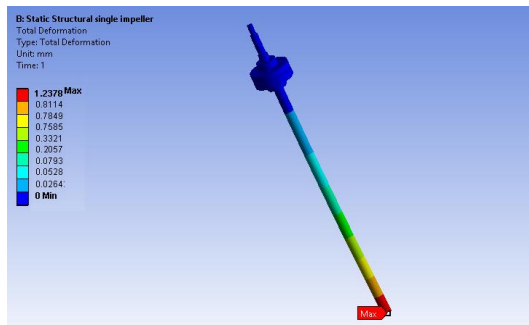**Figure 10** Equivalent / von-mises stresses of Double impeller Agitator shaft

Figure 11 Deformation of Double impeller Agitator shaft

Figure 12 Enlarge view of Max Equivalent / von-mises stresses of Agitator shaft

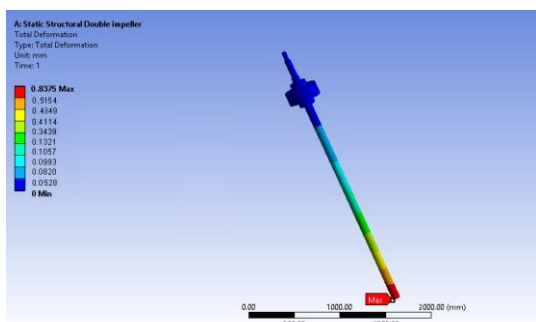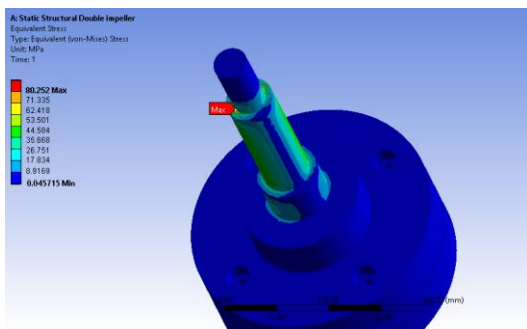**Figure 13** Equivalent / von-mises stresses of Single impeller Agitator shaft

Figure 14 Total Deformation of Agitator shaft
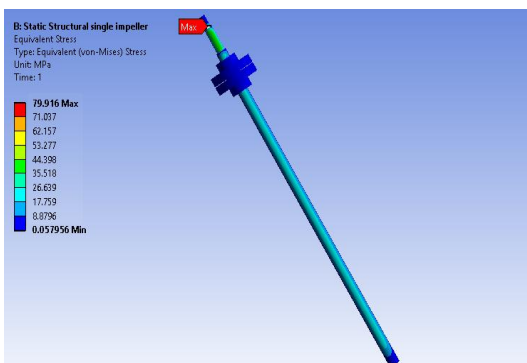

Figure 15 Enlarge View of Max Equivalent / von-mises stresses of Single impeller Agitator shaft

5. Results & discussions

Table 3 Design Modification

Sr. No.	Design Parameter	Modified	Previous
1.	Motor	15hp	10hp
2.	Material	SS316	Structural steel
3.	Diameter of shaft	90mm	60mm
4.	No. of impeller	Two	One
5.	Mounting of agitator	Top & Center	Eccentrically
6.	Baffle plates	Provided	No

Table 4 Equivalent stress by FEA & Analytical Approach

	Parameter	Unit	FEA Result	Analytical Result
1	Double impeller shaft	MPa	80.916	90.45
2	Single impeller shaft	MPa	79.916	85.68

Table 5 Deflection by FEA & Expt. Approach

Parameter	Deflection by FEA Method (mm)	Deflection by Expt.(mm)
Double impeller shaft	0.8375	0.8746
Single impeller shaft	1.237	1.469

Conclusions

In this dissertation work a methodology to analysis and design of Agitator shaft is presented. During this work following conclusions are found,

1) Selecting another material for agitator increase strength, ductility& corrosion resistance.
2) By increasing no. of impellers improves mixing time, provide balancing & reduce deformation.
3) By mounting agitator shaft at centre done provision for baffle plates in vessel.
4) Provision of baffle plates gives uniform mixing.
5) Equivalent Stress generated in double impeller shaft is approximately same as that of single impeller shaft.
6) Deflection in Double impeller shaft is less as compare that of single impeller shaft.
7) The deformation and Equivalent stress are within the permissible limit.

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